Loss Unbalance Issue of the Full-bridge Inverter with Reactive Power Injection

Zhongting Tang*, Yongheng Yang**, and Frede Blaabjerg*
*Department of Energy Technology, Aalborg University, Aalborg-9220, Denmark
**College of Electrical Engineering, Zhejiang University, Hangzhou-310027, China
E-mails: zta@et.aau.dk, yang_yh@zju.edu.cn, fbl@et.aau.dk

***Abstract*—The unbalanced power losses of the semiconductor switches affect the thermal loading, and thus, the reliability of power converters is challenged. In this paper, the unbalance loss distribution of power devices has been analyzed in a full-bridge (FB) PV inverter, which employs the traditional hybrid unipolar pulse width modulation (UPWM) for reactive power injection. This analysis serves to improve the design and control of the FB inverter to enhance its reliability. More importantly, a new modulation method is proposed to balance the power losses, resulting in good thermal performance and increase lifetime. The proposed method periodically changes the switching operation modes at the grid frequency to ensure equal power losses, and thus, the almost identical junction temperature of each power switch. Simulation and experimental results have validated the effectiveness of the loss analysis and the proposed modulation scheme.**

***Index Terms*—Loss unbalance, full-bridge inverter, hybrid PWM, circulated control**

I. INTRODUCTION

With the remarkable increase of installed renewables, e.g., wind and solar photovoltaic (PV) [1], reliability is becoming much stringent to ensure most energy generation with the least cost, i.e., low levelized cost of energy (LCOE) [2]. In grid-connected renewable energy systems (RESs), improved design and controls for high reliability should consider the inherent characteristics of renewables (e.g., large power fluctuations) and demands of the utility grid (e.g., active/reactive power regulation) [3], [4]. In addition, harsh environments may also affect the reliability performance, such as high ambient temperature and high humidity [5].

Taking the grid-connected PV system as an example, power converters play a critical role in energy conversion, being more vulnerable and of higher maintenance costs when compared to other parts, e.g., PV modules, connectors, and disconnects [6]–[9]. Consequently, many reliability-oriented designs and controls have been studied to improve the reliability of PV power converters [10]–[14]. For instance, in [12], the thermal performance of the critical components (i.e., the DC-link capacitor and power switches) in a PV inverter was analyzed, which is highly sensitive to the ambient temperature. A reliability-oriented design guideline for the input capacitor in single-phase transformerless PV inverters was introduced [13]. In addition, an MPPT control concept has been proposed to improve the thermal performance and to increase the utilization of PV energy in [14]. All efforts are aimed to decrease the failure rate of the fragile components and prolong the lifetime of the power converter with low costs.

A reliability prediction has shown that the DC-link capacitor and power switches are the main fragile components in PV inverters [11], [12], [15]. As a result, the reliability enhancement can be done through several aspects: 1) proper design of the heatsink, usually at the expense of power density and cost; 2) good power device layout [15]; 3) optimal switching-frequency [11]; 4) advanced controls (i.e., power control [14] and modulation methods [16]). Additionally, reactive power injection is now a must in PV systems for grid supporting capability, which can also challenge the reliability of PV inverters [17]–[19]. For example, in [19], a reliability analysis of reactive power provision by single-phase PV inverters has been presented. However, the thermal performance and reliability analysis were based on a bipolar modulation scheme, which was not commonly used due to high power losses [20].

The traditional hybrid unipolar pulse width modulation (UPWM) has a unbalance loss distribution for the full-bridge (FB) inverter [16], [21]. In that case, four power devices in the inverter have different thermal performance and failure rate [22], resulting in low reliability and causing more design costs. Hence, this paper analyzes the loss performance of the power devices for the conventional FB inverter in Section II, where the effect of the reactive power injection is also considered. More importantly, an improved hybrid modulation method with reactive power injection has been proposed to balance power losses among the devices in Section III. Simulations and experimental results are provided in Section IV, which verifies the analysis and the effectiveness of the modulation method. Finally, Section V gives concluding remarks.

II. LOSS AND THERMAL ANALYSIS

The semiconductor device is one of the fragile components of power converters [12]. Thus, prolonging the lifetime of the power devices has a significant for increasing the reliability of the power converter. For the power device, the junction temperature is an intuitive indicator of the reliability, and the main factors that caused high junction temperatures are high power losses and poor heat dissipation. In that case, the unbalanced power losses of power devices will result in different failure rates, and the power device of the highest

This work was supported by the Novo Nordisk Fonden through the Interdisciplinary Synergy Programme (Award Ref. No.: NNF18OC0034952).

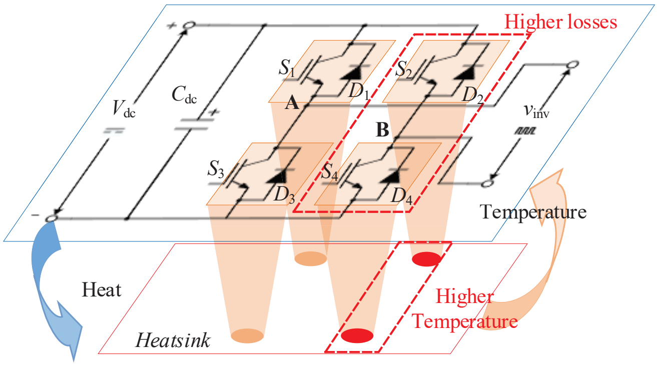

Fig. 1. Power loss distribution of an FB inverter under the traditional UPWM method.

failure rate decides the reliability of the entire power converter. Therefore, the reliability can be improved to some extent when all power devices can share losses equally. The loss unbalance issue is analyzed for the FB inverter in the following as well as the thermal distribution under the traditional UPWM.

A. Traditional UPWM for the FB inverter

Fig. 1 shows the power loss distribution of the FB inverter employing the traditional UPWM. The FB inverter has four switches of Insulated Gate Bipolar Transistors (IGBT) $S_{1\text{-}4}$ (with the anti-paralleled diodes $D_{1\text{-}4}$). In Fig. 1, C_{dc} represents the DC-link capacitor, V_{dc} is the DC-link voltage and v_{inv} is the modulated output voltage of the FB inverter.

To achieve reactive power injection and high efficiency, the traditional UPWM controls two switches (i.e., S_1, S_3) at the fundamental-frequency and the other two switches (i.e., S_2, S_4) are at a high-frequency transition, as demonstrated in Fig. 2. In addition, v_{ref} and i_{ref} are the reference voltage and current. Referring to the power losses of the semiconductor devices [23], there are switching and conduction losses, which can be given as

$$P_L = P_{sw} + P_C \tag{1}$$

where P_L is the power loss of one switch, P_{sw} and P_C represent the switching losses and conduction losses, respectively.

Moreover, the switching losses P_{sw} can be expressed as

$$P_{sw} = P_{swT} + P_{swD} = (E_{onT} + E_{offT} + E_{onD}) f_{sw} \frac{V_{ceav} I_{cav}}{V_{CC} I_{CC}} \tag{2}$$

where P_{swT} and P_{swD} are the switching losses of the IGBT and the anti-parallel diode, f_{sw} is the switching frequency, and E_{onT}, E_{offT}, and E_{onD} are the turn-ON, turn-OFF, and diode reverse-recovery energy, correspondingly, which are provided in the datasheet under certain test conditions (i.e., the test voltage V_{CC} and current I_{CC}). According to Eq. (1), the switching losses are mainly distributed at S_2 and S_4, as shown in Fig. 2. When considering conduction losses are equal in each power device, the unbalanced power losses can be compared in Table I. Since the fundamental frequency f_{fd} is far less than the high switching frequency (being above kHz level), the switching losses of S_1 and S_3 can be neglected.

Considering the reactive power injection, the conduction losses of the FB inverter are distributed among the IGBTs when generating positive apparent power, while the losses are distributed among the body diodes for negative apparent power. Thus, the conduction losses of IGBTs and diodes, i.e., P_{CT} and P_{CD} ($P_C = P_{CT} + P_{CD}$), can be calculated as

$$P_{CT} = \frac{1}{\pi}\int_0^{\varphi} \frac{V_m \cos\omega t}{V_{dc}} (V_{ce0} + r_c I_m \cos(\omega t + \varphi)) \\ I_m \cos(\omega t + \varphi) dt \tag{3}$$

$$P_{CD} = \frac{1}{\pi}\int_0^{\varphi+\pi} \frac{V_m \cos\omega t}{V_{dc}} (V_{d0} + r_d I_m \cos(\omega t + \varphi)) \\ I_m \cos(\omega t + \varphi) dt \tag{4}$$

where V_{ce0}, r_c, V_{d0} and r_d are the IGBT on-state zero-current collector-emitter voltage, the collector-emitter on-state resistance, the diode on-state zero-current voltage and the diode on-state resistance, φ is the power factor angle, V_m, I_m and ω are the amplitude of the AC output voltage and current, and angular frequency. Eqs. (2) and (3) imply that the conduction losses are unbalanced on the IGBTs and the diodes with different power factor angles, as presented in Fig. 2. In all, the power losses on the IGBTs and the diodes are unbalanced when the inverter enables reactive power injection with the traditional UPWM. This may affect the reliability of the entire system.

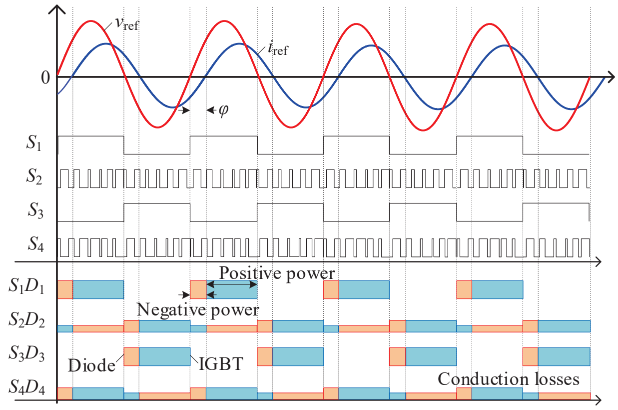

Fig. 2. Traditional UPWM strategy with reactive power injection for the FB inverter, where the orange part represents the power losses of diodes and blue part shows the power losses of IGBTs.

TABLE I
LOSS COMPARISON OF THE POWER DEVICES.

Switches	**Losses**
S_1, S_3	$P_C + (E_{onT} + E_{offT} + E_{onD}) f_{fd} \frac{2V_{dc} I_m}{\pi V_{CC} I_{CC}}$
S_4, S_4	$P_C + (E_{onT} + E_{offT} + E_{onD}) f_{sw} \frac{2V_{dc} I_m}{\pi V_{CC} I_{CC}}$

TABLE II
OPERATION STATES OF THE FB INVERTER FOR REACTIVE POWER INJECTION.

Operation state	Period	S_1	S_2	S_3	S_4
A	$v_{\text{ref}} > 0$	ON	↑↓	OFF	↑↓
B	$v_{\text{ref}} < 0$	OFF	↑↓	ON	↑↓
C	$v_{\text{ref}} > 0$	↑↓	OFF	ON	↑↓
D	$v_{\text{ref}} < 0$	↑↓	ON	OFF	↑↓

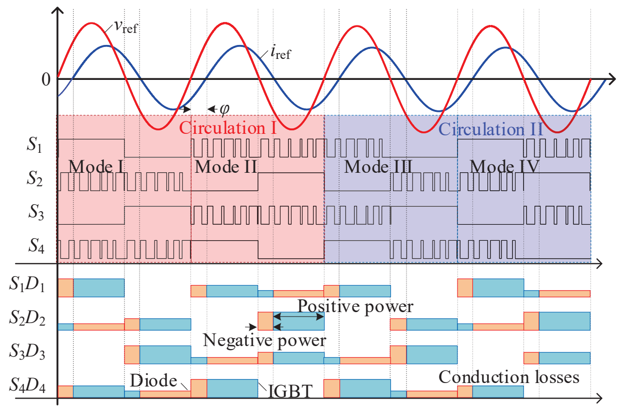

Fig. 3. Possible switching operations and the power losses distribution of the FB inverter.

III. PROPOSED MODIFIED UPWM

According to the above analysis, the unbalanced power losses of the power devices are mainly caused by the different switching frequencies. In addition, the internal IGBTs and body diodes have different conduction losses. To achieve a comprehensive balance of power losses, the solutions include improved modulation methods and redundant designs (adopting extra components to share the losses). Here, an improved hybrid modulation method for the FB inverter has been introduced when considering conduction losses of IGBTs and body diodes.

There are four operation states of the FB inverter to enable reactive power injection, as shown in Table II, where "↑↓" and "↓↑" represents complementary switch instants at a high switching frequency. When $v_{\text{ref}} > 0$, the FB inverter can operate at both states **A** and **C**, generating a positive voltage v_{inv}. While $v_{\text{ref}} < 0$, it can operate at both states **B** and **D** to generate v_{inv}. The four operation states are combined into four switching modes for the DC-AC conversion of the FB inverter, i.e., Mode I — states **A** and **B**, Mode II — states **C** and **D**, Mode III — states **A** and **D** and Mode IV — states **B** and **C**. The four switching modes are shown in Fig. 3. Obviously, the traditional UPWM in Fig. 1 only adopts Mode I, leading to unbalanced power losses on the semiconductor devices.

Therefore, a modified UPWM technique is proposed to ensure the loss equalization of IGBTs (i.e., $S_{1\text{-}4}$) and body diodes (i.e., $D_{1\text{-}4}$). A circulated control is adopted for the FB inverter to change the switching mode at a low frequency. It should be noted that the circulated time should be chosen

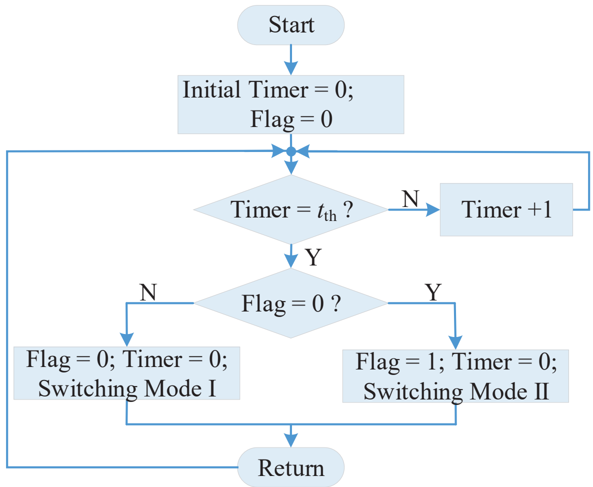

Fig. 4. Proposed circulated control method to balance the power losses for the FB inverter.

well to avoid large fluctuations of the junction temperature of the power devices. It is revealed in [22] that the constant junction temperature operation can maintain a long lifetime of the power devices.

There are two circulating paths to achieve so, i.e., Circulation I– Modes I + Modes II, and Circulation II – Modes III + Mode IV. Fig. 3 demonstrates the details of the proposed modulation method with the two circulation controls. The corresponding power loss distribution is also analyzed in Fig. 3, which illustrates that the power losses can be balanced among the IGBTs and the diodes. Fig. 4 then shows the proposed hybrid modulation method with the control of Circulation I (i.e., changing switching Mode I and Mode II). It can be seen in Fig. 4 that the FB inverter performs two different switching modes alternatively for every circulated period t_{th}, which is chosen as being the multiply of the grid fundamental cycle.

Consequently, the proposed method can ensure the equal power loss distribution of power devices in the FB inverter, improving reliability. When compared to the method of adding extra power components, the proposed modulation method slightly increases calculation burdens, while achieving relatively high cost-effectiveness.

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulation results

To verify the effectiveness of the power losses analysis and the proposed UPWM methods, simulations are carried out in PLECS. The thermal-loss models of the power devices are established based on the device datasheets (i.e., Infineon IGBT–IKW30N65ES5). The system parameters are the DC-link voltage $V_{\text{dc}} = 365$ V, the output AC voltage $v_{\text{ac}} =$ 220 V / 50 Hz (the root mean square-RMS), the output power $P = 5$ kW, and the switching frequency $f_{\text{sw}} = 20$ kHz. Moreover, the power factor φ is a variable between 0 to π.

Fig. 5 compares the power loss distribution between the traditional UPWM and the proposed modulation method, where the dotted curves are the results of the traditional

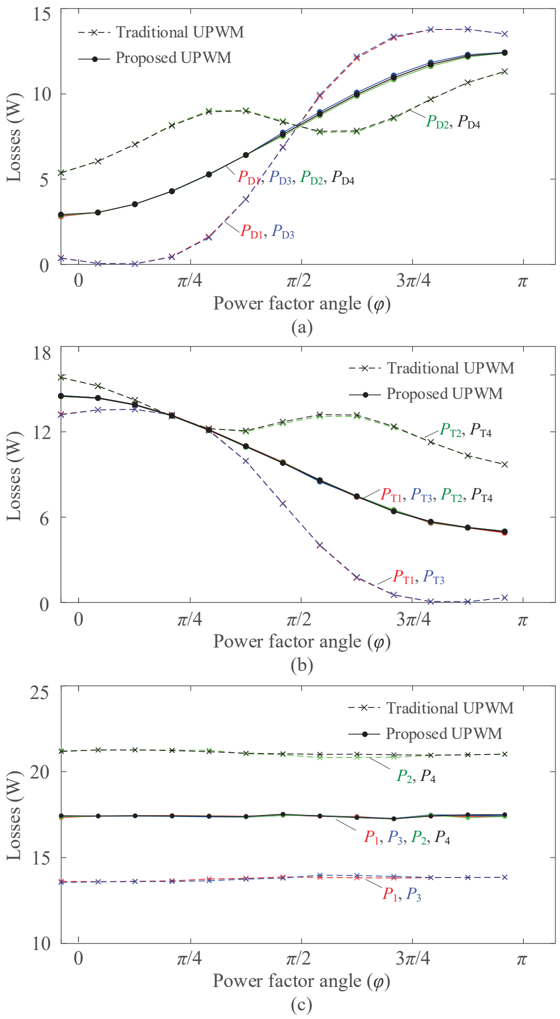

Fig. 5. Simulation results of the power losses distribution for the traditional UPWM and the proposed method with different power factors: (a) losses on bode diodes, (b) losses on IGBTs, and (c) losses on IGBTs + bode diodes.

UPWM method and the solid curves are that of the proposed modulation method. In the simulation results, $P_{D1\text{-}4}$, $P_{T1\text{-}4}$ and $P_{1\text{-}4}$ denote the losses of the body diodes, the IGBTs and the IGBTs + bode diodes. As shown in Figs. 5(a) and (b), the power losses of the body diodes and the IGBTs change with the power factor angle when the FB inverter adopts both the traditional UPWM and the proposed modulation method. This illustrates that the reactive power injection has a negative impact on the internal loss balance of the power device. This point can be considered when designing the power control for the FB inverter system.

In addition, the power losses of IGBTs and body diodes are not identical when the FB inverter employs the traditional UPWM, as depicted in Figs. 5(a) and (b). The total power losses of $S_{1,3}$ are less than those of $S_{2,4}$, see the dotted lines in Fig. 5(c). By contrast, the IGBTs losses, the body diodes losses and the total losses of $S_{1\text{-}4}$ are balanced with the proposed UPWM, as shown in Fig. 5. The comparison results verify that the proposed modulation method can achieve better performance than the traditional UPWM scheme in terms of power loss.

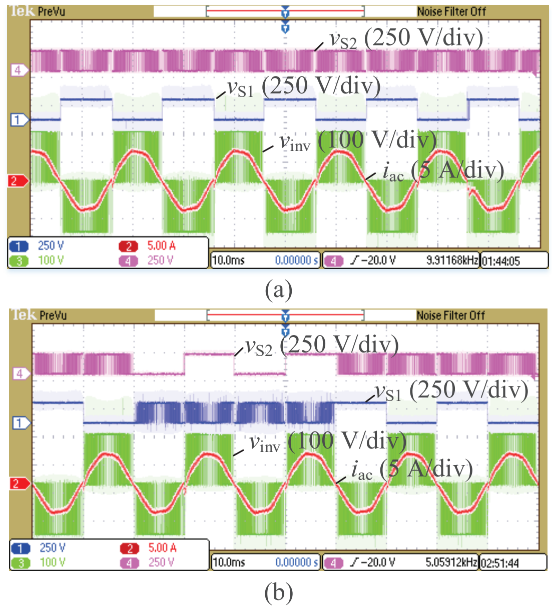

Fig. 6. Experimental comparison of the FB inverter (time: 10 ms/div): (a) the traditional UPWM and (b) the proposed UPWM.

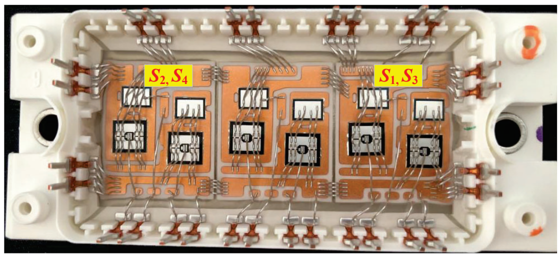

Fig. 7. Bird-view of the IGBT module for the FB inverter.

B. Experimental results

Experiments are carried on a 1-kW FB inverter, where V_{dc} is 250 V, v_{ac} is 110 V / 50 Hz (RMS), and the switching frequency f_{sw} is 20 kHz. Fig. 6 shows the experimental results of the FB inverter under the traditional UPWM and the proposed modulation methods. v_{S1}, v_{S2}, v_{inv} and i_{ac} represent the voltages of S_1 and S_2, the inverter differential voltage and the output AC current. As shown in Fig. 6(a), v_{S1} changes at the grid frequency and v_{S2} changes at a high switching frequency. However, the switching frequencies of v_{S1} and v_{S2} change alternatively with the proposed circulated UPWM scheme, as presented in Fig. 6(b). The circulated time is 40 ms, i.e., being two times the grid fundamental cycle. The results suggest that the proposed modulation scheme may tackle the loss unbalance issue of the FB inverter.

Fig. 7 shows the bird-view of the adopted module, i.e., IGBT module FS50R12KT4-B15. Two phase-legs of a three-phase power module are considered for better comparison due to the good consistency of switches on one power module. Fig. 8 compares the thermal performance between the traditional UPWM and the proposed modulation methods. As

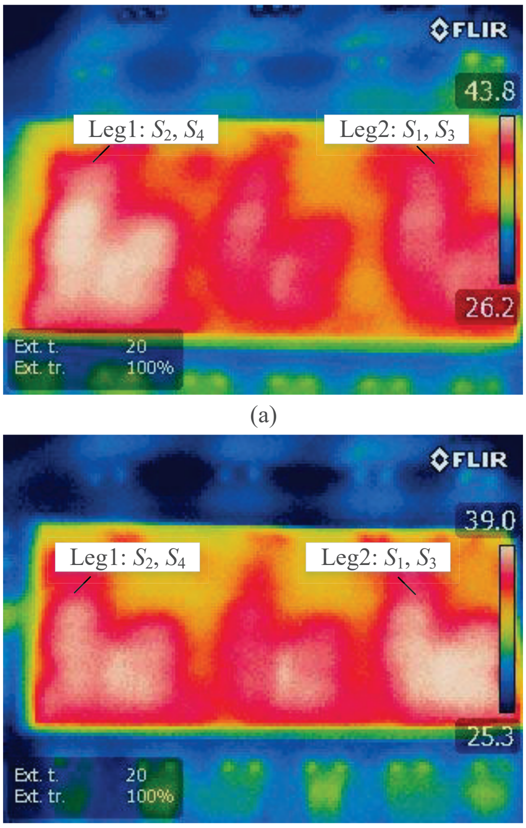

Fig. 8. Thermal performance of the FB inverter with: (a) the traditional UPWM, and (b) the proposed modulation method.

shown in Fig. 8 (a), the temperatures of $S_{2,4}$ are higher than those of $S_{1,3}$ when the inverter is employing the traditional UPWM method. While the temperatures of $S_{1\text{-}4}$ are almost identical when the FB inverter adopts the proposed UPWM, as demonstrated in Fig. 8(b). Besides, the highest temperature in Fig. 8(a) (i.e., adopting the traditional UPWM method) is higher than that in Fig. 8(b) (i.e., adopting the proposed UPWM method). It can be verified from the results that the proposed UPWM scheme can address the loss unbalance issue, achieving identical junction temperature of the power switches and increasing the reliability of the FB inverter.

V. Conclusion

In this paper, the loss unbalance issue has been analyzed for the FB inverter when the traditional UPWM method is adopted to achieve reactive power injection. It is revealed that the main reason for the unbalance problem is the switching frequency as well as the reactive power injection. Then, a modified UPWM scheme was proposed, which has two circulated ways to balance the losses of critical power switches even with the reactive power injection. The loss analysis and the proposed UPWM method have been verified through simulations and experiments, which confirms the performance of the proposed method to enhance the reliability of the FB inverter.

References

[1] F. Blaabjerg, Y. Yang, K. Ma, and X. Wang, "Power electronics - the key technology for renewable energy system integration," in *Proc. of ICRERA*, pp. 1618-1626, 22-25 Nov. 2015.

[2] H. Wang, F. Blaabjerg, K. Ma, and R. Wu, "Design for reliability in power electronics in renewable energy systems – status and future," in *Proc. of ICPEEED*, pp. 1846-1851, 13-17 May 2013.

[3] F. Blaabjerg, Y. Yang, D. Yang, and X. Wang, "Distributed power generation systems and protection," in *Proc. of IEEE*, vol. 105, no. 7, pp. 1311–1331, Jul. 2017.

[4] IEEE Standard Committee, "IEEE standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces," *IEEE Std 1547-2018*, pp. 1-138, Apr. 2018.

[5] F. Blaabjerg, K. Ma, and D. Zhou, "Power electronics and reliability in renewable energy systems," in *Proc. of ISIE*, pp. 19-30, 28-31 May 2012.

[6] G. Petrone, G. Spagnuolo, R. Teodorescu, M. Veerachary, and M. Vitelli, "Reliability issues in photovoltaic power processing systems," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2569-2580, July 2008.

[7] H. Huang and P. A. Mawby, "A lifetime estimation technique for voltage source inverters," *IEEE Trans. Power Electron.* , vol. 28, no. 8, pp. 4113-4119, Aug. 2013.

[8] J. Flicker and S. Gonzalez, "Performance and reliability of PV inverter component and systems due to advanced inverter functionality," in *Proc. of PVSC*, pp. 1-5, 14-19 Jun. 2015.

[9] "A review of PV inverter technology cost and performance projections," Navigant Consulting, Inc., Burlington, MA, NREL Subcontract Rep. NREL/SR-620-38771, Jan. 2006.

[10] A. Ristow, M. Begovic, A. Pregelj and A. Rohatgi, "Development of a methodology for improving photovoltaic inverter reliability," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2581-2592, Jul. 2008.

[11] E. Koutroulis and F. Blaabjerg, "Design optimization of transformerless grid-connected PV inverters including reliability," *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 325-335, Jan. 2013.

[12] M. Catelani, L. Ciani, and E. Simoni, "Thermal analysis of critical components in photovoltaic inverter," in *Proc. of I2MTC*, pp. 1891-1895, 13-16 May 2012.

[13] H. Wang, Y. Yang, and F. Blaabjerg, "Reliability-oriented design and analysis of input capacitors in single-phase transformer-less photovoltaic inverters," in *Proc. of APEC*, pp. 2929-2933, 17-21 March 2013.

[14] Y. Yang, H. Wang, F. Blaabjerg, and T. Kerekes, "A hybrid power control concept for PV inverters with reduced thermal loading," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6271-6275, Dec. 2014.

[15] U. Choi, I. Vernica, and F. Blaabjerg, "Effect of asymmetric layout of IGBT modules on reliability of motor drive inverters," *IEEE Trans. Power Electron.*, vol. 34, no. 2, pp. 1765-1772, Feb. 2019.

[16] L.U. Sudha, J. Baskaran, and S. Thamizharasan, "Hybrid PWM strategies for power balance in H-bridge inverter," in *Proc. of ICCPEIC*, pp. 536-539, 16-17 Apr. 2014

[17] C. J. Muray, A. Davoudi, and P. L. Chapman, "Reliability analysis for single-phase photovoltaic inverters with reactive power support," in *Proc. of IPEC*, pp. 1-6, 25-26 Feb. 2011.

[18] S. M. Sreechithra, P. Jirutitijaroen, and A. K. Rathore, "Impacts of reactive power injections on thermal performances of PV inverters," in *Proc. of IECON*, pp. 7175–7180, 10-13 Nov. 2013.

[19] A. Anurag, Y. Yang, and F. Blaabjerg, "Thermal performance and reliability analysis of single-phase PV inverters with reactive power injection outside feed-in operating hours," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 3, no. 4, pp. 870-880, Dec. 2015.

[20] Z. Tang, M. Su, Y. Sun, B. Cheng, Y. Yang, F. Blaabjerg, and L. Wang, "Hybrid UP-PWM scheme for HERIC inverter to improve power quality and efficiency," *IEEE Trans. Power Electron.*, vol. 34, no. 5, pp. 4292-4303, May 2019.

[21] R. Lai and K. D. T. Ngo, "A PWM method for reduction of switching loss in a full-bridge inverter," *IEEE Trans. Power Electron.*, vol. 10, no. 3, pp. 326-332, May 1995.

[22] U. Scheuermann and S. Schuler, "Power cycling results for different control strategies," *Microelectron. Reliab.*, vol. 50, no. 9-11, pp. 1203-1209, Sep.-Nov. 2010.

[23] G. Dušan and P. Marco, IGBT Power Losses Calculation Using the Data-Sheet Parameters, 1st ed., Neubiberg, Germany: Infineon, 2009, pp. 5–6.